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A PCB-Embedded Pressure Sensor for Wireless Wind Sail Monitoring

A.Rossetti [1*], R.Codeluppi [2], A.Golfarelli [2], M.Zagnoni [4], A.Talamelli [1] and M.Tartagni [3]

[1]DIEM – Mechanical, Nuclear, Aviation and Metallurgical Engineering, Second School of Engineering, University of Bologna, Italy
[2]SORTRON s.r.l. Via Saba 541, 47522 Cesena - Italy
[3]ARCES - Advanced Research Center on Electronic Systems, Second School of Engineering, University of Bologna, Italy
[4]Department of Electronic and Electrical Engineering, University of Glasgow, G128LT, Glasgow, UK

Abstract

A capacitive differential pressure sensor suitable to be implemented in a wireless sensor network has been designed, built, and experimentally tested. The pressure sensing unit is implemented in a printed circuit board (PCB) technology based on a thin 3D triple layers structure composed of: a pre-stressed polymeric diaphragm, woven glass reinforced epoxy resin (FR4) and metal layers. Aim of the developed sensor network is to sense the pressure field acting on the surface of a full battens sail by means of instrumented battens. Inside any instrumented batten an appropriate number of wireless nodes are mounted, the pressure sensing units is integrated in any wireless node, acting as pressure measurement spot. The sensor network is targeted to provide a real time differential pressure map over the sail surface. The pressure sensing unit behavior has been modeled using finite element simulations. By means of a static non-linear coupled mechanical-electrostatic model, has been possible to predict the pressure versus capacitance static characteristic and to tune the geometry of the transducer to reach the required resolution, sensitivity and time response in the appropriate full scale pressure input, ranging from +/- 250 Pascal.

Keywords: capacitive pressure sensors; fluid-dynamics; wireless sensor networks.

Introduction

Until a few years ago, sail design was developed experimentally through trial-and-error practice of sail makers. More recently, aerodynamic numerical methods (implementing potential flow, lifting-surface, vortex-lattice methods) have been used. All these methods are computationally efficient but limited to preliminary design. More accurate numerical prediction can be performed by means of Reynolds averaged Navier-Stokes solvers (RANS) [1-2], however a large computational power is required. Experimental studies have been performed on both two-dimensional sails and three-dimensional full yacht models [3-4]. Wilkinson performed an experimental database in the form of pressure measurement on a two-dimensional rigid mast-sail model varying different parameters, [5-6]. Wind-tunnel results on 3D models are useful, but the actual flying shape of sails is difficult to be reproduced because of the soft materials from which they are made, the difficult problem of rig structural similitude, and the absence of wind-gradient effects in most wind tunnels. Thus, the ability to acquire differential pressures on a sail, operating in the changeable environment, would make a breakthrough in sail design. In our approach, any

* Corresponding author: Alessandro Rossetti, Second School of Engineering, University of Bologna (IT), Campus of Forlì, Via Fontanelle 40, I-47100 Forlì, Tel.: +39-0543-786928; *e-mail address*: arossetti@arces.unibo.it.

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instrumented batten enables the acquisition of differential pressure across the sail chord from the sail luff to the leech, according to the number of wireless nodes present in the battens. By combining the measurements of each batten, it is possible to map the pressure profile at different height along the mast (Fig. 1(a), 1(b)).

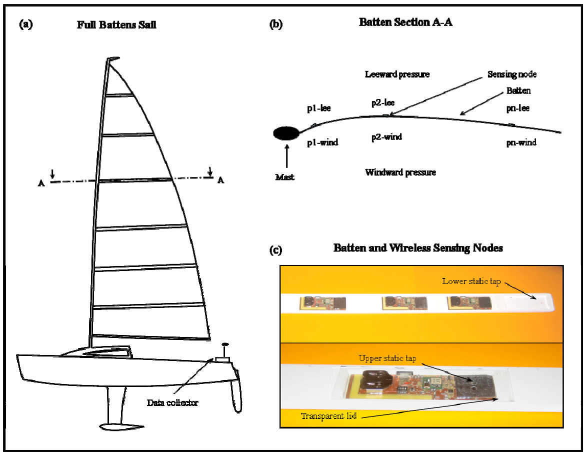

Figure 1: Full batten sail (a), batten section (b), wireless nodes (c).

Pressure range	±250 [Pa]	Autonomy	50 days, 8h/day
Transceiver	Zensys ZW2102		
Capacitance sensor range	2.08 [pF]	Average Power cons.	100 [µA]
Mean sensitivity	4.16 [fF/pA]	Measured range	50-80 [m]
Tested resolution	1.08 [pA]	Maximum number of nodes	20
Single node data acquisition period	60 [ms]	Entire network acquisition period	3 [s]

Table 1: Specifications of the wireless sensor network

1. Pressure profile acquisition approach

The network is composed of three main elements: a pressure-sensing unit, a wireless sensor network node and the instrumented battens. Instrumented battens are positioned on the sail surface (Fig.1a) where they are inserted inside special pockets and presents, in the proximity of each nodes two static taps (Fig.1c). The upper tap connects the pressure of the leeward side of the sail to the top of the sensing unit, whilst the lower tap the pressure of the windward side to the bottom of the device so that the differential pressure $\Delta p_i = pi_{lee} - pi_{wind}$ is depicted along the battens, being pi_{lee} and pi_{wind} the static pressure acting across the sail surface on the i-th wireless node. Each wireless node comprises a capacitive pressure sensor positioned in the forward side, as illustrated in Fig.1, and linked to the board by means of a 2mm thick plinth of FR4 on which it is bonded, as will be explained in the next section. The electrical capacitive sensing is based on a charge amplifier interfaced with a microcontroller for managing electronic phases and for data processing to be transmitted by the transceiver with data rate of about 9.6 kbps. The antenna is an "L-shaped" λ/4 monopole created directly on the PCB and it has been tuned for a transmission frequency of 868MHz. Nodes transmit the acquired differential pressure to a data collector located in the yacht deck and the system is able to handle about twenty nodes (Fig. 1(a)). Any instrumented batten enables the acquisition of differential pressure Δp_i distribution across the sail chord from the sail luff to the leech, according to the number of wireless nodes placed on the battens. By combining the measurements of each batten, it is possible to map the pressure profile at different height along the mast. The main characteristics of the network are summarized in Table.1.

2. Pressure sensor structure

The pressure sensor, implemented in each node, is basically a capacitive pressure sensor fabricated in PCB technology. The use of PCB technology is preferred for low fabrication costs, sensor robustness to harsh environments and allows the hosting of electronic sensing and signal processing components by means of smart packaging (such as the chip-on-board technology). The sensing unit consists of a three-layered structure in a stack, as shown in Fig.2: a base, a spacer and a diaphragm. The base layer is a rigid, woven fibreglass epoxy (760µm thick), copper-clad (35µm thick), composite layer. On the top side, a circular copper electrode with a radius of 2.8mm is obtained, representing the lower fix plate of the sensor capacitor. On the bottom side, a guard ring is designed for reducing parasitic effects, whilst two pads enable the connection to the electronics on the wireless node. A circular static tap of 1mm of radius (Fig. 2b) is drilled in the base layer. The static tap acts also as an electric via, allowing further connection to the electronics. A semicircular via was also obtained on the edge of the base layer to contact the conductive diaphragm by means of conductive glue, as shown in Fig. 2(a)-(c)-(d). The spacer is a fibres-glass FR4 layer (125µm thick). A circular cavity (that outlines the shape of the electrode on the base layer) is drilled in the spacer Fig.2d, creating a volume in which the diaphragm can deflect according to pressure loads applied. The sensing diaphragm consists of 12µm thick Mylar840® (DuPont) conductive film that acts as the second plate of the sensor capacitor.

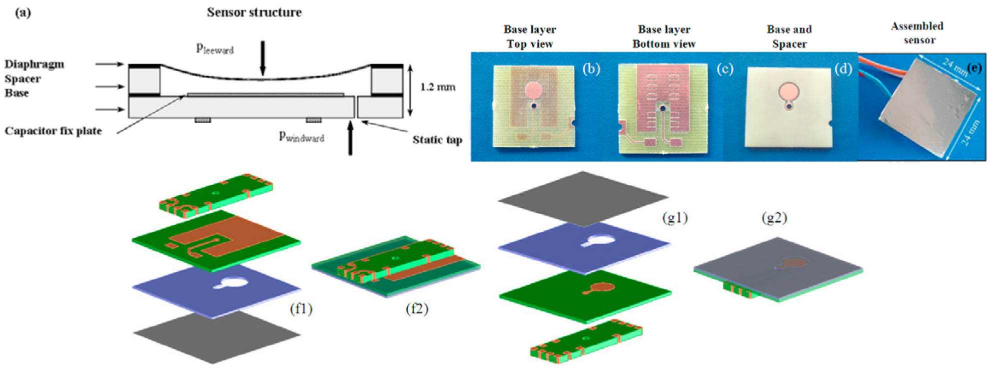

Fig. 2. (a) Sensor cross section, (b) base layer top view, (c) base layer bottom view, (d) base and spacer layer assembled, (e) assembled sensor. (f) Exploded and, (g) assembled triple layer structure.

3. Modeling

In order to model the sensor characteristics for an optimal design, a finite element method (FEM) approach has been used for coupling the mechanical and electrostatic problem. The electrostatic module receives the deformed shape of the diaphragm as an input geometry and solves the Poisson's equation in order to calculate the sensor capacitance. The mechanical parameters used in the simulation were obtained from data sheet and are reported in the following table:

Material	Young's Module (Gpa)	Poisson's Ratio
Copper	115	0.22
FR4	70	0.25
Mylar®	5	0.30

Table 1. mechanical properties of materials for finite element analysis.

The Mylar840® diaphragm is coated on the bottom side with an aluminium deposition of few Armstrong, FEM simulations show that the mechanical behaviour of the diaphragm is not affected by such layer. As previously demonstrated [7], the diaphragm behaviour follows the "large deflection" model and our approach can accurately predict the sensor behaviour. This effect produces non-linearities between stresses and deflection. Most importantly, the mechanical deflection of the thin polymeric film is affected by the amount of pre-stress induced during the fabrication process of the sensing units, which has been implemented as parameter in the boundary conditions.

4. Results and discussion

Experimental tests have been performed at the wind tunnel. By means of a Pitot tube has been possible to get the required differential pressure input, in the range +/- 250 Pascal. In order to apply several constant differential pressure values, a device with two sealed chamber has been fabricated, thus the diaphragm has been loaded with the dynamic pressure of the flow. The actual value of the dynamic pressure in the test section sensed by means of the Pitot tube was measured with a high accuracy commercial pressure transducer Setra®, while the related value of the transduction output of the capacitor was measured by means of an Agilent 4284A Precision LCR meter.

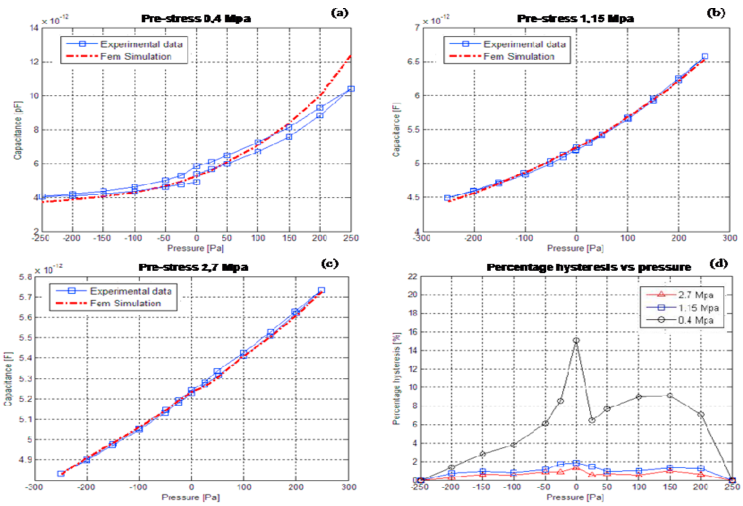

Fig. 3: Static characteristic for three different pre-stressed diaphragm; 0.4 MPA (a), 1.15 MPa (b), 2.7Mpa(c), percentage hysteresis (d)

Three sensing units have been fabricated with three different pre-stress of: 0.4 MPa, 1.15 MPa 2.7 MPa. Comparisons between FEM simulations and static experimental results show that predictions are reliable when the pre-stress of the diaphragm is greater than 0.4 Mpa, as shown in Fig 3(b) and (c). Agreement between the experimental data and the numerical simulations confirms that the FEM static model is a suitable tool to predict the sensor characteristics when the value of pre-stress is above a certain threshold, to reduce hysteresis effect on the membrane, thus demonstrating a versatile approach for a rapid prototyping of PCB-based capacitive pressure sensors.

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